Bioelectric Notes
Note 3
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Focusing an Electromagnetic Implosion Inside Tissue

Carl E. Baum and Serhat Altunc
University of New Mexico
Department of Electrical and Computer Engineering
Albuquerque, New Mexico 87131

Karl H. Schoenbach and Shu Xiao
Frank Reidy Research Center for Bioelectrics
Old Dominion University
Norfolk, VA 23510

Abstract

Previous attention has been given to focusing a fast electromagnetic pulse (an electromagnetic implosion) on a target at the surface of a dielectric, such as tissue. Here we consider some of the problems and design options for focusing on more deeply buried targets.

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1. Introduction

Considerable progress has been made toward focusing a narrow electromagnetic pulse (an electromagnetic implosion) on the surface of tissues (e.g., skin in the case of skin cancer) [1,2]. In this case, going to high dielectric constants in the lens helps to more narrowly focus the pulse, and correspondingly increase the field on target.

Another case of interest concerns more deeply buried targets. How does one go about focusing a pulse there, and how small a beam is achievable for a given (unipolar) pulse width?

2. Surface Focusing

A. Lens spot-size decrease and electric-field increase

As discussed in [3,4], surface focusing is dominated by the properties of the lens which is in contact with the tissue surface. Without going into detailed calculations (which can make a factor of a few difference in the results), the spot size is governed by the pulse width: 100 ps corresponds to 3 cm at the speed of light in vacuum. So one might expect a concentrated spot size of this order. A radius of about

$$r_{spot}^{(0)} \cong \frac{a}{b} ct_{\delta} \tag{2.1}$$

has been estimated [1], where a and b are the two radii prolate-spheroidal reflector. As we can see from this formula, if ε_r is increased, the wave speed is decreased by $\varepsilon_r^{½}$ giving

$$r_{spot} \cong r_{spot}^{(0)} \varepsilon_r^{-\frac{1}{2}} \cong \frac{a}{b} ct_{\delta} \varepsilon_r^{-\frac{1}{2}} \tag{2.2}$$

Electrodynamic scaling indicates a more concentrated spot size and higher electric field as one increases the lens final dielectric constant ε_{rmax} from 1.0. Dimensions scale inverse to the propagation speed, i.e. as $\varepsilon_{rmax}^{-½}$. So we have

$$l_{\varepsilon} = \frac{spot\ \ size\ \ with\ \ \varepsilon_{r\,max} >> 1}{spot\ \ size\ \ with\ \ \varepsilon > 1} = \varepsilon_{r\,max}^{-\frac{1}{2}} \tag{2.3}$$

$$S_{\varepsilon} = spot\ \ area\ \ factor \propto l_{\varepsilon}^{2} = \varepsilon_r^{-1}$$

For our example with $\varepsilon_r = 81$ (water) we have

$$\text{Spot radius} = \frac{3cm}{\varepsilon_r^{1/2}} \cong 3.3mm \tag{2.4}$$

Conserving power on the wavefront (lens thick enough (with zero dispersion) for negligible reflection) gives an increase in power density

$$f_p = \frac{area\ \ in}{area\ \ out} = S_{\varepsilon}^{-1} = \varepsilon_r \cong 81 = \frac{power\ \ density\ \ out}{power\ \ density\ \ in} \tag{2.5}$$

The power density for

$$E = Z_w H \tag{2.6}$$

$$Z_w = (\frac{\mu_0}{\varepsilon})^{\frac{1}{2}} = \varepsilon_r^{-\frac{1}{2}} Z_0$$

$$Z_0 \cong 377\Omega$$

(plane wave approximation, good in the high-frequency limit), goes like

$$P = \frac{1}{2}\vec{E} \times \vec{H} = \frac{E^2}{2Z_w} = \varepsilon_r^{1/2} \frac{E^2}{Z_0} \tag{2.7}$$

Thus we have

$$\frac{P_{out}}{P_{in}} = \varepsilon_r^{1/2} \frac{E_{out}^2}{E_{in}^2} = f_p = \varepsilon_r \tag{2.8}$$

$$f_E = \frac{E_{out}}{E_{in}} = \varepsilon_r^{1/4}$$

which, for our example, gives

$$\varepsilon_r = 81, \quad f_E = 3 \tag{2.9}$$

which is a significant E-field increase.

B. Electric-field increase in passing from lens to a lower permittivity

If the target medium is the same as the lens medium at ε_{rmax} we would expect by symmetry the beam to have a narrow waist at the target followed by a diverging beam similar to the converging beam. However, if, as in Fig. 2.1, we have

$$\varepsilon_{rt} \equiv \text{target medium relative permittivity}$$

$$< \varepsilon_{max} \tag{2.10}$$

so that we are stepping from a higher to a lower ε_r, then we may expect a more rapidly diverging beam.

Near the interface, however, we can still roughly estimate the electric field in the target medium as an enhancement given by (r for target medium, ℓ for lens medium)

$$T_E = \frac{2Z_{wt}}{Z_{wt} + Z_{wl}} = 2[1 + [\frac{\varepsilon_{rt}}{\varepsilon_{rl}}]^{1/2}]^{-1} \tag{2.11}$$

For example, if

$$\varepsilon_{rl} = 81 \text{ (water)} \tag{2.12}$$

$$\varepsilon_{rt} = 16$$

then we have

$$\left[\frac{\varepsilon_{rt}}{\varepsilon_{rl}}\right]^{1/2} = \frac{4}{9} \tag{2.13}$$

$$T_E = \frac{18}{13} \cong 1.4$$

This indicates some possible benefit of increasing the lens permittivity over the target-medium permittivity. It reduces the spot size and increases the electric field. Note that the above electric-field enhancement is based on a plane-wave approximation. As such, it should only be considered as an approximation.

C. Decrease of electric field into target medium

As one goes into the target medium, the diverging beam decreases the electric field (and power density). So moving the target location deeper into the tissue can be problematical. How deep can one go before this decrease takes over? Clearly this depth is of the general order of the spot radius (as in (2.4)).

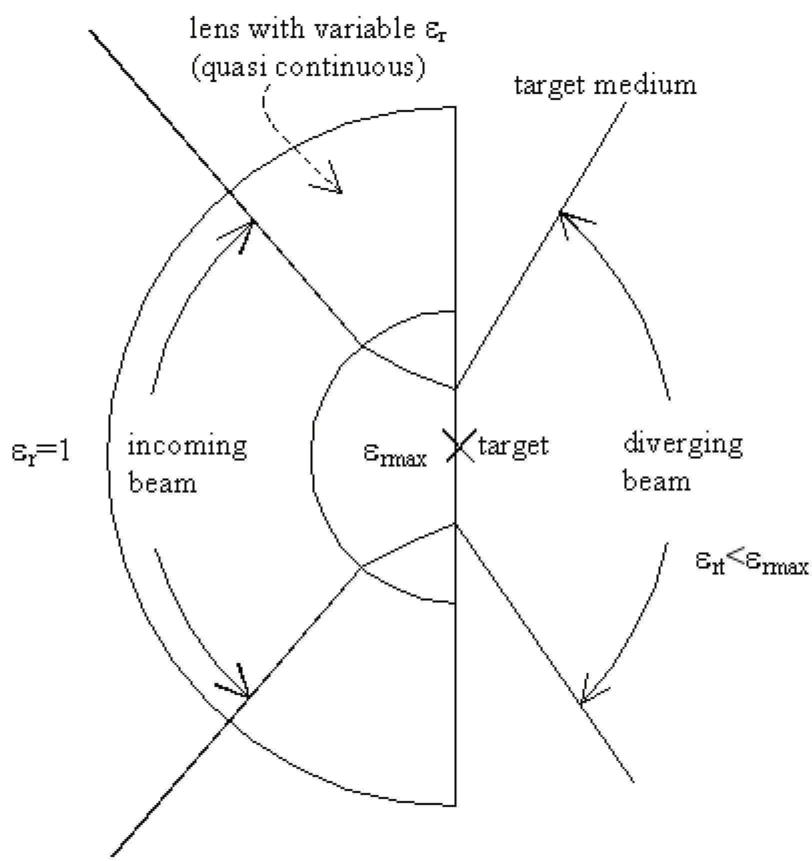

Fig. 2.1 Launching a Wave From the Lens Medium Into a Lower-Permittivity Target Region

3. Matching Lens and Tissue Permittivities for Deep Focusing

For deep focusing we can imagine a spherically incoming pulse (an electromagnetic implosion) in the target medium. The focusing estimates are like the previous, except that now ε_{rt} dominates the calculations. The spot size from (2.2) looks like

$$r_{spot} = r_{spot}^{(0)} \cong \frac{a}{b} \varepsilon_{rt}^{-\frac{1}{2}} ct_\delta \tag{3.1}$$

so that ε_{rt} limits how small we can make the spot size. One can also try to reduce a/b (characterizing the beam convergence), but going from 1.2 to a lower limit of 1.0 does not help much. (It would also increase the prepulse with opposite polarity [1].)

In this case, the spot size is limited by the target-medium permittivity and the electric-field enhancement is limited as in (2.8). For example

$$\varepsilon_{rt} = \varepsilon_{r\,max} = 16 \Rightarrow f_E = \varepsilon_r^{\frac{1}{4}} = 2 \tag{3.2}$$

which could still be useful.

In order to better focus the beam on the buried target, one might like to stretch the tissue transversely so as to shrink the depth to the target, at least to some degree. One can also reshape the tissue surface near the target to better focus the beam at the target depth. Figure 3.1 shows a possible concept for improvement in these respects. In this case, we hollow out the lens near the focus (say as a hemispherical or spheroidal cavity). The tissue surrounding the target is then sucked into this cavity by several small-diameter tubes drilled through the lens media to the lens/tissue interface. The medium between the lens and tissue might be gas or oil. By applying a vacuum, the tissue can be sucked into the cavity (perhaps with some limits on the size/shape of the cavity). This will require some detailed engineering.

By this technique, one can increase the solid angle through which the electromagnetic wave can approach from the lens to the target. Together with transverse stretching (dilation), this can reduce the dispersion of the pulse as it approaches the target.

This technique is perhaps limited to not-too-deeply-buried targets. As one goes to deeply buried targets, one will need to make the radius of the lens aperture sufficiently large compared to the depth. This will, in turn, increase the overall lens radius.

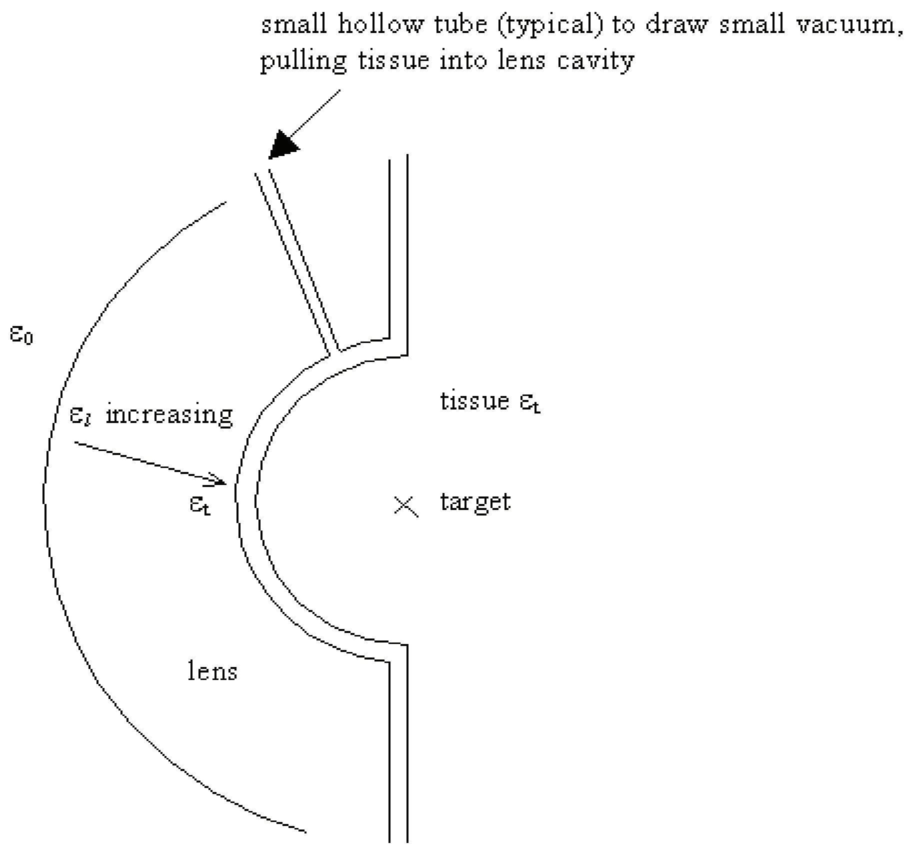

Fig. 3.1 Drawing Pliable Tissue Into Lens Region

4. Concluding Remarks

There are then various techniques one can employ to focus electromagnetic pulses on buried targets, such as targets in tissue. For deeply buried targets, there are various problems to consider, including attenuation and dispersion. However, these can sometimes be mitigated by techniques, such as those discussed above.

References

1. C.E. Baum, "Focal Waveform of a Prolate-Spheroidal Impulse-Radiating Antenna," Radio Science, Vol. 42, RS6527, 2007.

2. S. Altunc, C.E. Baum, C.G. Christodoulou, E. Schamiloglu, and C.J. Buchenaur, "Focal Waveforms for various source waveforms driving a prolate-spheroidal impulse radiating antenna (IRA)," Radio Science, Vol. 43, RS4513, 2008.

3. C. E. Baum, "Addition of a Lens Before the Second focus of a Prolate-Spheroidal IRA " Sensor and Simulation Note 512, April 2006.

4. S. Altunc, C. E. Baum, C. G. Christodoulou and E. Schamiloglu "Lens Design for a Prolate Spheroidal IRA", Sensor and Simulation Note 525, Oct 2007.